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Overuse Injury Assessment Model

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14. ABSTRACT
This report describes the first year's progress towards the development of a bone stress fracture model. A literature review was conducted to determine the current state of research and develop regression equations to estimate necessary gait parameters. U.S. Marine Corp Basic Training recruit and regime data was acquired and organized for input into a model. The initial stress fracture algorithm was based on a theoretical model published in the literature that accounts for micro- and macro-crack growth.

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Table of Contents

1. Executive Summary

The high cost in both lost days and medical expenses due to stress fractures during basic training has led to several studies identifying factors that increase the likelihood of developing an injury. Unfortunately, the risk factors identified are not based on the mechanisms involved in the injury and, thus, extrapolating their results to novel situations is limited. The approach documented in this report is a mathematical model based on observed properties of bone and bone damage (Overuse Injury Model 1.0), an advantage that should allow the model to be used in different situations. A concerted effort was made to establish realistic parameters and values.

A literature review revealed that most areas of bone health have been studies, there are bone damage models of varying complexity, and that there is a stress fracture paradox. *In vitro* studies indicate that under physiological loading levels, the number of cycles to failure is well beyond that seen during military training. Thus, the stress fractures that occur must be a result of higher concentrated stresses, possibly due to the repair process initially weakening bone, and several investigators hypothesize that the training regime is an important element the stress fracture process.

In this report, regression equations were developed to convert common training regime measures such as distance and speed for walking and running to bone stresses. U.S. Marine Corp Depot basic training data for females at Parris Island and males at San Diego were acquired, organized, and quantified for input into the model. Although only a small portion of the available measures was utilized in this model, details for all measurements are presented for reference. A CD is included with a copy of the descriptions of the data collected on the U.S. Marines.

Overuse Injury Model 1.0 was based on "Bone Maintenance and Remodeling: A Control System Based on Fatigue Damage," a theory proposed by Taylor (1997). The advantages of this model include accounting for micro- and macro-crack growth rates and a simple constant repair rate. Using the acquired Marine Corp data and a Monte Carlo simulation, the model was able to simulate the cumulative fracture rate for both the female and male data but different bone stress parameters were used. Nevertheless, the model was stable, the overall trend was in agreement with the observed data, and the results were qualitatively better than using training distances alone.

There are several recommendations for model improvement, which primarily emphasize higher quality input data. Additional training regimes and a more standardized method of quantifying the regimes, such as direct measurement using sensors, would allow direct comparisons between training regimes as well as more sophisticated optimization routines to modify the model. Two additional datasets have been found for model to simulate and the principal investigators have been contacted. Also, bone shape adaptation (bone modeling) is a known response to loading and has not been included in the current version of the model. In conclusion, the model appears capable of predicting stress fractures and with additional modification, further improvements can be expected.

2. Introduction

Overuse injuries is a concern in the military and the high cost, both in lost days and medical expenses, has triggered an effort to better understand this type of injury. The current focus of this project is stress fracture from overuse. The cost due to stress fractures among 2,000 female Marine recruits alone is estimated to be $1,850,000 annually with 4,120 lost training days (Subcommittee on Body Composition Nutrition and Health of Military Women 1998). This example also serves to highlight that especially at risk are women, whose increasing participation in the Services have led to an increased injury rate (Kowal 1980; Jones et al. 1999) and illuminated the need for new training regiments to accommodate this population.

Current approaches have focused on correlations and risk analysis to determine the important factors affecting the likelihood of having a stress fracture for various military training groups. Unfortunately, without understanding the underlying mechanical process causing injury, the utility of identifying risk factors is limited. It is not possible to reliably extrapolate these results to different populations, simulate different regimes, or aid in equipment design.

Our approach to the stress fracture problem is to account for the known mechanical response of bone through mathematical models. The primary reason for this approach is that it incorporates the underlying stress or loads, the fundamental cause of injury and performance. If implemented correctly, this technique will allow new regimes and equipment to be tested for injury potential, hopefully reducing the number of actual stress fractures seen during training.

This report describes our initial progress to meet the following objectives:

- Develop a Overuse Injury Model 1.0 (OIM 1.0) capable of predicting stress fracture injury
- Identify, acquire, and quantify inputs needed for model
- Determine the feasibility of the model to predict stress fracture
- Identify key areas for improvement

To achieve these objectives, a literature review was conducted to determine basis for the first model and acquire the necessary data. Although the exact form of the model and the required inputs were not initially known, several general areas were identified after a

broad literature review (Figure 2-1). After finding different bone damage models of varying complexity, it was clear that any mechanistic model's inputs would be based on the magnitude of the load and the number of times the load was applied. Regression equations to estimate bone stress as well as the number of steps (load cycles) for walking and running based on speed and distance were developed. Regime data was acquired with sufficient details to estimate the number of miles or time marched and ran for each day of basic training. In addition, day of stress fracture injury was acquired for model comparison.

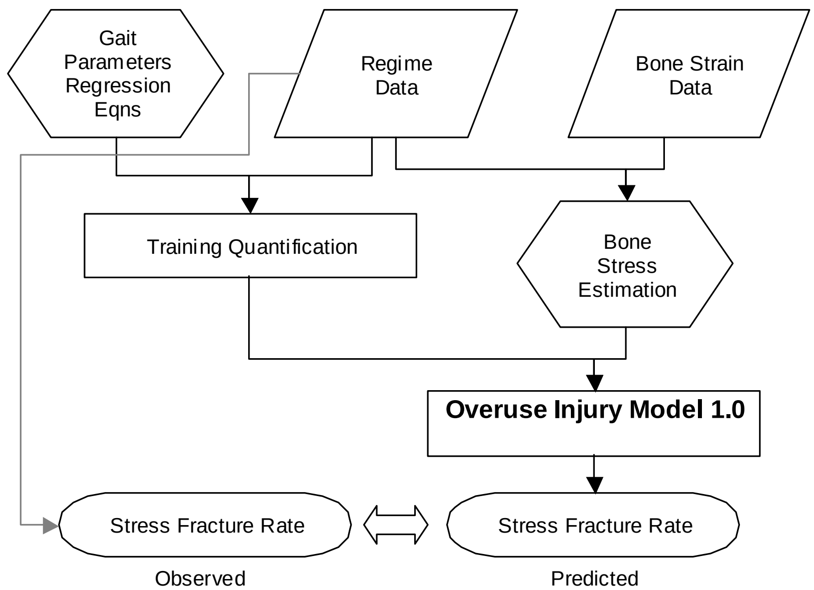


Figure 2-1 A chart diagramming the flow of data utilized in the development of Overuse Injury Model 1.0. Using regime data and other model inputs estimated from the literature, stress fracture rate was predicted and compared to the observed fracture rate.

3. Literature Review

3.1 An overview of current trends of bone health and stress fracture research in the military

The purpose of this section is to provide a fundamental (biomechanical) overview of bone and to briefly summarize the current research regarding bone health and military training, identifying known risk factors and paradigms.

3.1.1 Concepts of bone and bone damage

A general overview of some of the important bone structures and process of damage are covered here; readers are encourage to refer to other publications for more information (e.g., Cowin 1982; Hall 1995; Rho et al. 1998; Whiting and Zernicke 1998; Burr and Milgrom 2001). Bone is a dynamic porous structure that serves many functions such as load bearing, protection, and calcium regulation. There are two types of bone, which is classified depending on the porosity: trabecular and compact bone. In general, trabecular (also known as cancellous or spongy bone) is found in the spine and the ends of long bones. Porosity is 75-95%. More dense compact bone is found in the shafts of long bones as well as encasing vertebral bodies and other spongy bones. In adult humans, most compact bone is comprised of cylindrical structures known as secondary osteons or Haversion systems, which is bone that has been laid down by basic multicellular units (BMU's). The boundary between the osteon and the surrounding bone is known as the cement line.

The material properties of bone is dependent on the shape, porosity, mineralization and density of the bone. In addition, bone is viscoelastic and stronger when loaded more rapidly. It is also stronger under compressive rather than tensile loading. An important measure is the elastic modulus, whose value changes with porosity (Martin 1991) but is approximately 17.5 GPa for compact bone under tension. Another common measure is bone mineral density (BMD), which may be correlated to strength.

Bone damage is the result of loading and can be measured in a number of different ways such as change in elastic modulus or crack propagation. Bone adapts to the loads placed on it (Wolff's Law) in two ways: modeling and remodeling. Modeling is the addition of new bone, whereas remodeling involves resorption and reformation of bone. Remodeling also removes and replaces damaged bone. BMU's are primarily responsible for damage removal and replacement of bone. However, this process can temporarily increase porosity

and cause bone to weaken further. Also, the mechanisms that the body uses to determine whether bone adaptation occurs is unknown.

3.1.2 Known bone health factors

Studies to numerous to mention have identified several factors that affect bone damage and Figure 3-1 shows a theoretical pathway based on these factors that leads to stress fracture. It is important to note that the primary pathway is mechanical in nature—loading forces are transmitted through the body and bone damage is dependent on the load and the material properties of the bone.

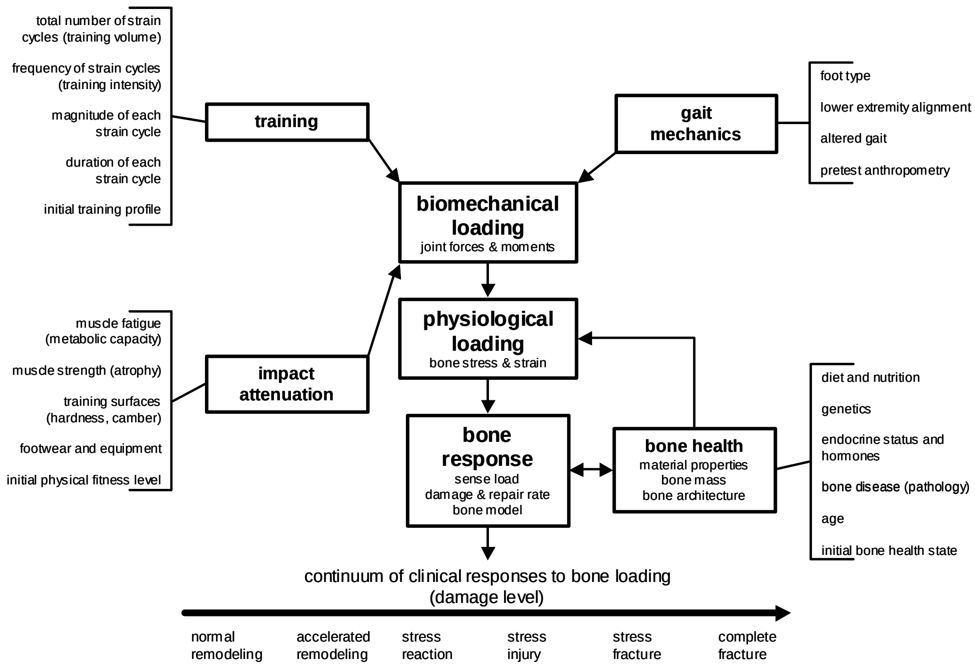


Figure 3-1 Known bone heath determinants. Modified from: Subcommittee on Body Composition Nutrition and Health of Military Women (1998). <u>Reducing Stress Fractures in Physically Active Military Women</u>. Washington, D.C., National Academy Press.

A review of the literature (see Table 3-1 for a sample) revealed that most areas of bone health outlined in Figure 3-1 have been studied and several trends have been identified. First, material testing indicates normal loading conditions are not sufficient to explain the number of stress fractures seen during basic training (i.e., a stress fracture paradox). Second, training magnitude appears to affect fracture rate, supporting the pathway in Figure 3-1, but additional data is needed for a complete analysis of training. Third, the utility of BMD measures as a predictor of stress fracture is questionable as there are other factors confounding the results. And fourth, biomechanical gender differences may be able to explain the higher injury rate observed in females.

Table 3-1 A sample of the research publications that relate to stress fracture injury. Virtually all areas of stress fracture have been studied. Direct biomechanical factors are highlighted including training (yellow) as well as impact attenuation and gait mechanics (blue). To date, only risk factor analyses have been performed and a biomechanical model incorporating some or all of the injury determinants has not been found.

Research Sample

Injury Determinants

		Almeida 1999	Beck 1994	Beck 2000	Carlson 1996	Donahue 1999	Friedman 1991	Giladi 1985	Hurwitz 1999	Reducing Stress Fractures 1999	Jones 1994	Kelly 2000	Lappe 2001	Lauder 1999	Leveston 1994	McCreadie 2000	Pollock 1997	Popovich 2000	Reinker 1979	Schaffler 1994	Scott 1999	Shaffer 1999	Stacy 1984	Stein 1999	Zeiss 1996	totals	percent
Biomechanical Loading	General																										
	Joint Forces								x												x					2	1%
	Joint Moments								x												x					2	1%
Physiological loading	General		x			x								x												3	2%
	Stress		x																		x			x	x	4	2%
	Strain		x			x																				2	1%
	Muscle		x																		x					2	1%
Bone response	Repair rate														x											1	1%
	Modeling																										0%
	Remodeling														x										x	2	1%
	Bone model	x											x		x			x							x	5	3%
Damage level	General																								x	1	1%
	Normal																										0%
	Accelerated																										0%
	Stress reaction																										0%
	Stress injury																										0%
	Stress fracture																										0%
	Fracture																			x					x	2	1%
Training	General	x			x		x	x		x	x			x	x	x		x	x				x			12	7%
	Initial profile							x			x			x								x				4	2%
	Volume	x					x	x			x			x			x	x					x		x	9	5%
	Intensity							x			x			x				x					x			5	3%
	Magnitude						x											x							x	3	2%
	Duration																										0%
Impact attenuation	General																										0%
	Initial fitness			x	x					x		x	x					x				x				7	4%
	Fatigue					x				x								x			x					4	2%
	Strength					x				x								x			x					4	2%
	Training Surfaces																										0%
	Footwear & equipment						x												x				x			3	2%
Gait mechanics	General											x														1	1%
	Anthropometry			x														x	x							3	2%
	Foot type																										0%
	Alignment						x																			1	1%
	Gait						x					x														2	1%
Bone Health	General																										0%
Bone properties	General																										0%
	Mass			x					x			x	x	x											x	6	4%
	Architecture			x			x																	x	x	4	2%
	Porosity																								x	1	1%
	Moduli			x																					x	2	1%
Influences	General																										0%
	Initial health										x	x	x					x				x				5	3%
	Nutrition									x			x									x				3	2%
	Genetics			x	x							x	x					x						x		6	4%
	Hormones									x		x	x													3	2%
	Disease																										0%
	Age											x	x					x						x	x	5	3%
	Smoking history									x		x	x					x				x				5	3%
	Weight			x					x			x	x						x					x		6	4%
	Height			x					x			x							x					x		5	3%
Damage location	General	x		x								x	x	x				x	x			x				8	5%
	Tibia			x			x	x																		3	2%
	Femur			x			x	x																		3	2%
	Metatarsal						x	x																		2	1%
	Fracture Rate	x		x	x		x	x			x	x	x					x	x			x	x			12	7%
	totals	5	4	12	4	4	11	8	5	8	6	13	12	7	4	1	1	15	7	2	6	7	5	6	13	168	
	Percent	3%	2%	7%	2%	2%	7%	5%	3%	5%	4%	8%	7%	4%	2%	1%	1%	9%	4%	1%	4%	4%	3%	4%	8%		

As noted by many researchers (e.g., Fyhrie et al. 1998), there is a stress fracture paradox—*in vitro* studies indicate that the number of cycles to failure under physiological loads is greater than the estimated number of load cycles during basic training by a factor of 5. For tensile loads (where bone is weaker), the number of cycles to failure is reduced but still indicates that bone strength is more than adequate for the loading conditions of basic training. Assuming the *in vitro* studies are valid, this suggests that the loading conditions are complex and bone stresses (and strains) may be much higher than anticipated. Some possible explanations why *in vivo* estimations may be low are 1) high localized stress levels that were not measured and 2) other nonmeasured movements may produce higher values (Burr et al. 1996; Ekenman et al. 1998). For example, it is well established that bone is weaker in tension than compression (Cowin 1982) and that muscle fatigue may lead to higher bone tension (Donahue 2001). However, it is not clear if strain levels change enough after fatigue to cause stress fractures (Yoshikawa et al. 1994; Donahue and Sharkey 1999). Another possible explanation is that bone remodeling, which is designed to repair damage, may further weaken bone in areas of marginally high strain, causing accelerated damage. The likely cause of this weakening is bone loss due to increases in porosity during the initial repair process (Zioupos et al. 1996). In addition, bone remodeling has been observed within the first couple of weeks of increases strains (Cowin 1983). Thus, additional, more subtle, loading conditions may elevate stress and play an important role in stress fractures.

Several studies hypothesize that training distances and/or intensity are related to injury (see Jones et al. 1994; Bennell et al. 1999 for a review). However, the exact relationship has not been determined and a comparison between regimes is difficult. Most studies suggest an increase or sudden change in the exercise regime such as experienced by the onset of basic training lead to increase injuries (Powell et al. 1986; Zahger et al. 1988; Pester and Smith 1992; Rudzki 1997; Almeida et al. 1999b; Jones and Knapik 1999; Pope 1999; Kelly et al. 2000; Lauder et al. 2000). Others found minimal differences in injury rates with changes to the training regime (Orava et al. 1978; Giladi et al. 1985; Garcia et al. 1987; Swissa et al. 1989; Taimela et al. 1990; Jones et al. 1993; Shaffer et al. 1999; Popovich et al. 2000). While some significant correlations between training and stress fracture rates have been found (Rudzki 1997; Almeida et al. 1999b; Pope 1999; Kelly et al. 2000; Lauder et al. 2000; Popovich et al. 2000), this type of analysis is regime-specific and cannot account for or be used to recommend future protocols.

Development of a model to compare various training regimes and to predict injuries requires both the training regime and time of injury as well as a standardized method of quantifying the data. Thus, consistent daily training logs and medical records are required. Unfortunately, publications investigating training effects that contained a complete biomechanical analysis or enough details for a complete analysis were not found. However, a few studies appear to collect the necessary data (Giladi et al. 1985; Almeida et al. 1999a; Shaffer et al. 1999; Popovich et al. 2000) and two data sets were acquired from the Naval Health Research Center. Organization and quantification of the Naval regimes for use in the overuse injury model is described in Chapter 4.

While bone mineral density (BMD) has become a popular measure of a bone's health, it's predictive capability is suspect and other measures may be more important. BMD is relatively easy to measure and has been shown to be related to the fracture toughness of bone (Martin 1991). However, its utility in predicting stress fractures due to overuse is suspect because of accuracy problems and the small differences in BMD seen between normal and stress fracture cases (Ross 1993; McCreadie and Goldstein 2000). Other measures such as bone porosity (Zioupos 2001) and bone geometry (Finestone et al. 1991; Stein et al. 1998; Beck et al. 2000; Zioupos 2001) appear to be important factors as well.

As noted previously, females recruits are more prone to injury than their male counterpart; several biomechanical factors have been identified. For example, women have smaller bones and less bone area (Stein et al. 1998; Beck et al. 2000), which may translate to higher local bone stresses. In addition, poor initial fitness level increased male and female stress fracture rate similarly (Canham et al. 1996), suggesting that lower aerobic fitness (and, thus, muscle fatigue) of some female recruit groups are responsible for the higher injury rate.

In summary, there is a large body of research pertaining to stress fractures but the lack of a concerted effort to understand the biomechanics of the injury make combining the existing research difficult. Nevertheless, there is sufficient evidence that biomechanics plays an important role in stress fracture injuries and that models based on biomechanics is a logical way to combine relevant research.

3.2 Regression equations to estimate gait parameters

Development of OIM 1.0 requires the quantification of the regime in order to estimate the load magnitude and frequency that the bone is subject to during training. Although direct measurement of bone stress for a large group is unfeasible, it may be possible to estimate the loading on bone from the ground reaction forces (GRF) delivered to the feet. Thus, a literature review was conducted whose purpose was to develop regression equations relating speed to possible correlates of bone stress: ground reaction forces and foot timing measures.

3.2.1 Methods

Twenty-eight publications were found that related peak GRF's (vertical, braking, propulsive), foot contact time, step length, and/or step rate to velocity for both walking and running. Note that peak vertical GRF's for walking consisted of two peaks. Using a spreadsheet program, GRF's and timing measures were plotted versus velocity. Standard deviations, if available, were also included. GRF's were normalized to total mass, which was body mass except for a few experiments where an external load was carried. The best fit regression equation based on the greatest correlation coefficient of determination (R^2) was found. Running style (forefoot or rearfoot strike), external load, gender, and foot wear were also monitored for their effect.

3.2.2 Results

The regression equations predicting ground reaction forces and timing measures from velocity for running and walking can be found in Table 3-2.

For running, GRF's and step length can be reasonable predicted from regression equations but foot contact time was more variable. See Figure 3-2 and Figure 3-3. Minimal differences were seen in peak GRF's between fore- and rear-foot strikers. Load and gender did not affect running timing measures appreciably as well.

For walking, the velocity for studies analyzing GRF's covered a narrow range for most of the publications except for Breit and Whalen (1997). Therefore, a regression equation was not developed. However, Breit and Whalen (1997) found a linear relationship between GRF's and velocity for a wide range of speeds and was in agreement with other studies (Figure 3-4). This equation is included in Table 3-2. Like running, step contact time was highly variable and the regression equation is of limited use. However, step length and

rate can be reasonably predicted from the equations (R^2 = ~0.85 for both step length and rate). Normalized GRF's and timing measures were not substantially affected by external load, gender, or footwear.

3.2.3 Discussion

The literature review of the GRF's and timing measures for walking and running revealed that some measures are readily repeatable, despite differences in gender, load, and footwear. This may allow the use of regression equations to estimate gait measures for those studies where these values are missing.

Although some of the regressions developed resulted is a strong correlation coefficient, there is individual variability as shown in the standard deviation error bars. While no effort was made to predict the deviation, the figures presented give some idea as to the level of individual variability for GRF's (Figure 3-2 and Figure 3-4). Because of the higher number of data points available to calculate the gait timing variables, standard deviations were not presented. However, the predictability of these variables can be easily seen from mean values presented (Figure 3-3 and Figure 3-5).

The results from this literature review indicate another use for the regression equations: verification of experimental setup. Referring to the Peak Vertical GRF plot of Figure 3-2, the GRF's presented by Dixon et al. (2000) is well below the typical vertical forces seen and may be due to calibration errors or experimental setup. Thus, the regression equations can be used as simple indicators, highlighting unknown errors that can be corrected prior to data collection.

Overall, the low variability of vertical GRF's and step length for both walking and running suggest that regression equations can be used when these measurements are missing. In addition, the equations may aid in identifying experimental errors.

Table 3-2 Regression equations to predict ground reaction forces and timing measures from velocity for running and walking. Velocity range from which the regression equations were derived is also listed.

Description	Units	Equation	R^2	V (m/s)	References
Running					
Ground Reaction Forces					
Peak Vertical	BW	$y = -0.0491v^2 + 0.5632v + 1.2958$	0.9255	1.5-6.0	Munro et al. 1987; Nilsson and Thorstensson 1989; Crossley et al. 1999; Hamill et al. 1984; Chang et al. 2000
Peak Braking	BW	$y = -0.0114v^2 + 0.165v - 0.074$	0.9937	1.5-6.0	Nilsson and Thorstensson 1989; Crossley et al. 1999; Chang et al. 2000
Peak Propulsive	BW	$y = -0.0072v^2 + 0.1435v - 0.0857$	0.9991	1.5-6.0	Nilsson and Thorstensson 1989; Crossley et al. 1999; Chang et al. 2000
Timing					
Contact Time	sec	$y = 0.4362e^{-0.1535v}$	0.7464	1.5-6.0	Hamill et al. 1984; Nilsson and Thorstensson 1989; Farley and McMahon 1992; Minetti et al. 1994a; Roberts et al. 1998; Wank et al. 1998; Chang and Kram 1999; Wright and Weyand 2001
Step Length	m	$y = -0.0213v^2 + 0.4537v - 0.0582$	0.9779	1.5-6.0	Cavanagh and Kram 1989; Craib et al. 1994; Minetti et al. 1994a; Svedenhag and Sjodin 1994; Brisswalter et al. 1996; Wank et al. 1998; Chang et al. 2000; Wright and Weyand 2001
Step Rate	step/s	$y = 0.0124v^2 + 0.0375v + 2.4823$	0.6406	1.5-6.0	Cavanagh and Kram 1989; Craib et al. 1994; Minetti et al. 1994a; Svedenhag and Sjodin 1994; Brisswalter et al. 1996; Wank et al. 1998; Chang et al. 2000; Wright and Weyand 2001
Walking/Marching					
Ground Reaction Forces					
Peak 1st Vertical	BW	$y = 0.4632v + 0.5208$	---	0.9-2.3	Breit and Whalen 1997
Peak 2nd Vertical	BW	$y = 0.2069v + 0.8201$	---	0.9-2.3	Breit and Whalen 1997
Peak Braking	BW	$y = 0.1495v + 0.0086$	---	0.9-2.3	Breit and Whalen 1997
Peak Propulsive	BW	$y = 0.1876v - 0.0550$	---	0.9-2.3	Breit and Whalen 1997
Timing					
Contact Time	sec	$y = 0.7336v^{-0.4254}$	0.5561	0.9-3.0	Murray et al. 1970; Jansen et al. 1982; Chao et al. 1983; Hamill et al. 1984; Martin and Nelson 1986; Nilsson and Thorstensson 1989; Martin and Marsh 1992; Borghese et al. 1996
Step Length	m	$y = -0.0329v^2 + 0.3736v + 0.2631$	0.8527	0.25-3.0	Murray et al. 1970; Jansen et al. 1982; Burdett et al. 1983; Chao et al. 1983; Hamill et al. 1984; Martin and Nelson 1986; Nilsson and Thorstensson 1989; Martin and Marsh 1992; Minetti et al. 1994b; Minetti et al. 1995; Borghese et al. 1996; Donelan and Kram 1997; Hangland and Cimbalo 1997; Kerrigan et al. 1998; White et al. 1998
Step Rate	step/s	$y = 1.6333v^{0.4964}$	0.8543	0.25-3.0	Murray et al. 1970; Jansen et al. 1982; Burdett et al. 1983; Chao et al. 1983; Hamill et al. 1984; Martin and Nelson 1986; Nilsson and Thorstensson 1989; Martin and Marsh 1992; Minetti et al. 1994b; Minetti et al. 1995; Borghese et al. 1996; Donelan and Kram 1997; Hangland and Cimbalo 1997; Kerrigan et al. 1998; White et al. 1998

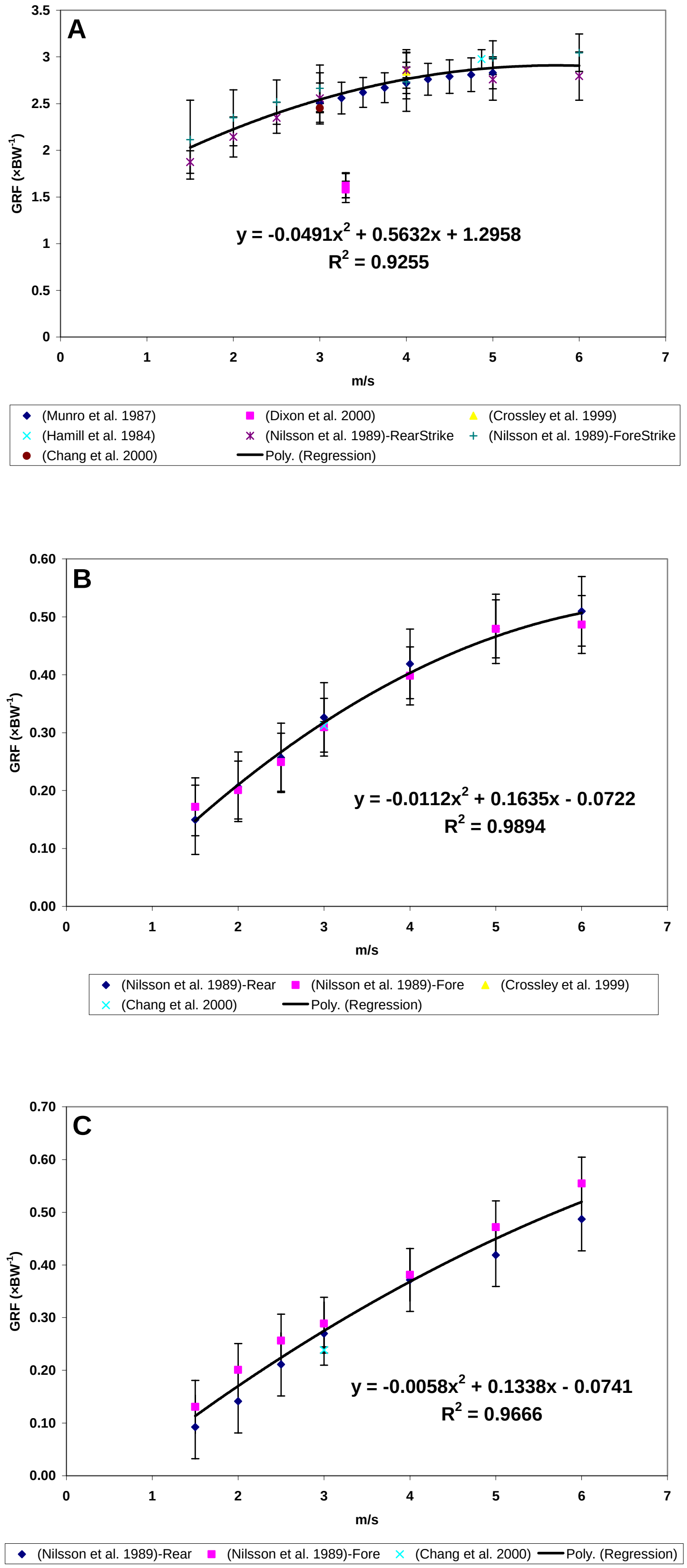


Figure 3-2 Peak vertical (A), braking (B), and propulsive (C) ground reactions forces (GRF) while running versus speed from a variety of publications. Reported standard deviations are included. Calculated regression line and equation relating GRF to running velocity are also shown. Note that the regression equation for vertical GRF does not include Dixon et al. (2000) because their reported values were outliers.

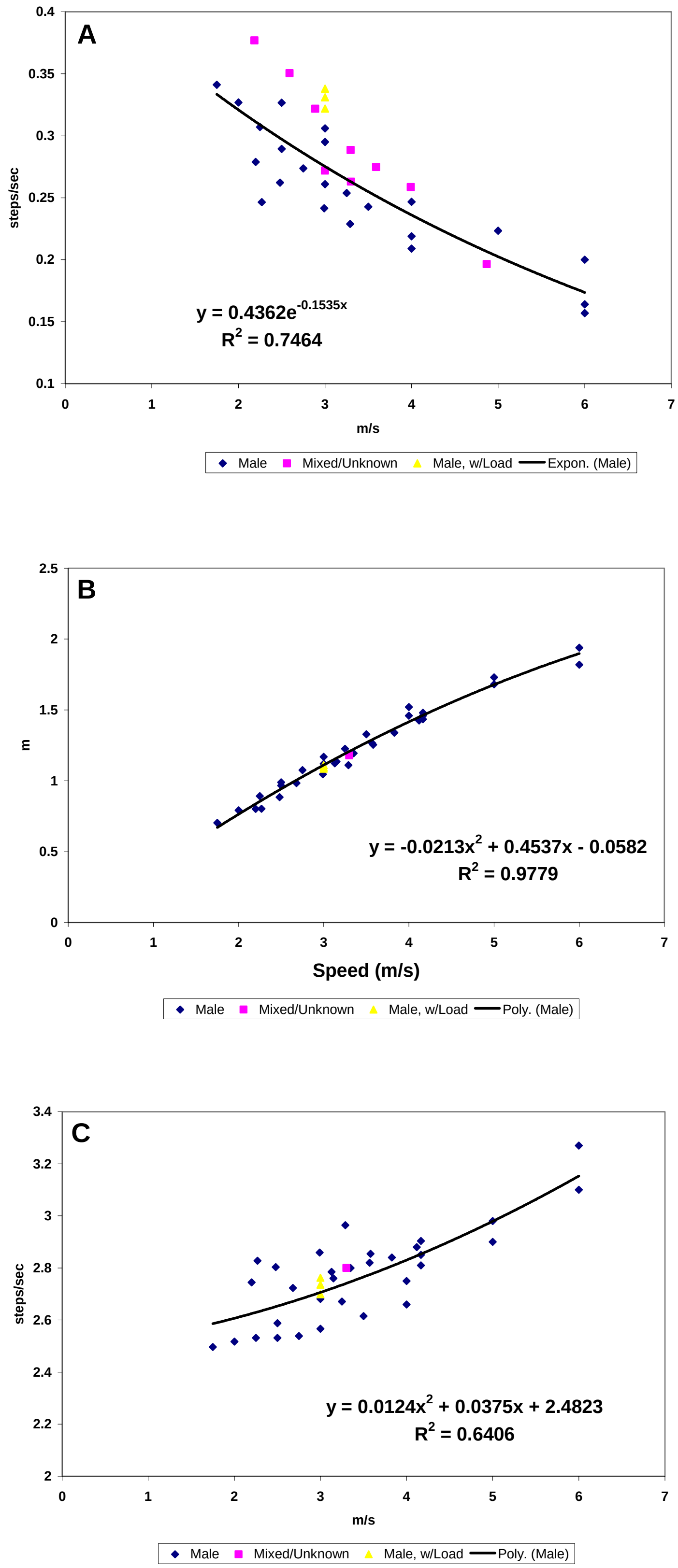
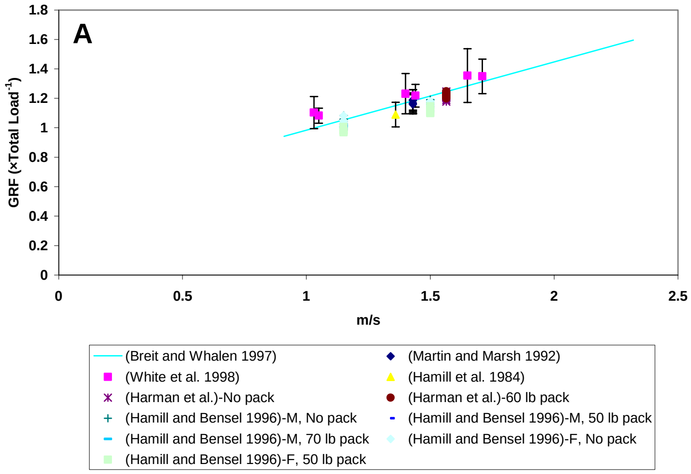
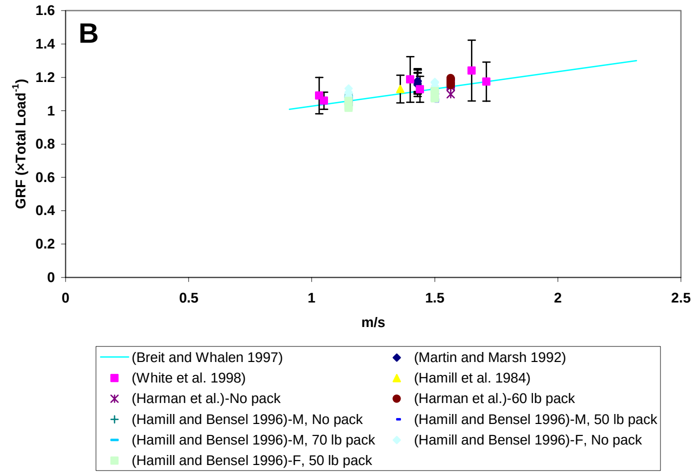


Figure 3-3 Foot contact time (A), step length (B), and step rate (C) while running versus speed from a variety of publications (Hamill et al. 1984; Cavanagh and Kram 1989; Nilsson and Thorstensson 1989; Farley and McMahon 1992; Craib et al. 1994; Minetti et al. 1994a; Svedenhag and Sjodin 1994; McLaughlin and Roush 1995; Brisswalter et al. 1996; Roberts et al. 1998; Wank et al. 1998; Chang and Kram 1999; Chang et al. 2000; Wright and Weyand 2001). Data found was predominantly from male subjects. The results suggest that gender and load have a limited effect on timing measures. Calculated regression line and equation relating timing measures to running velocity are also shown.





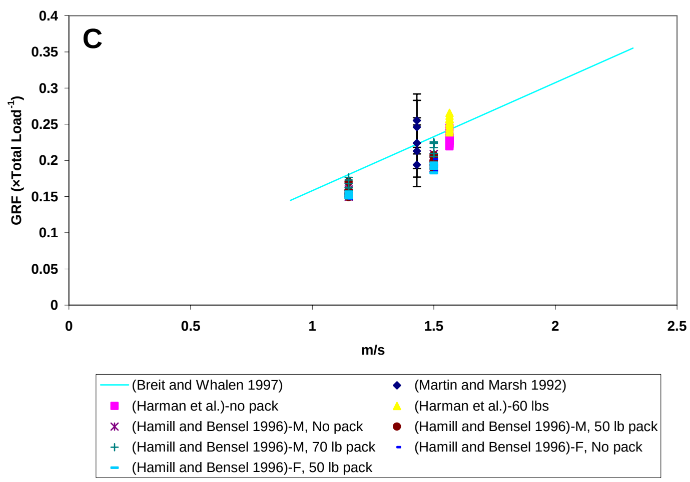
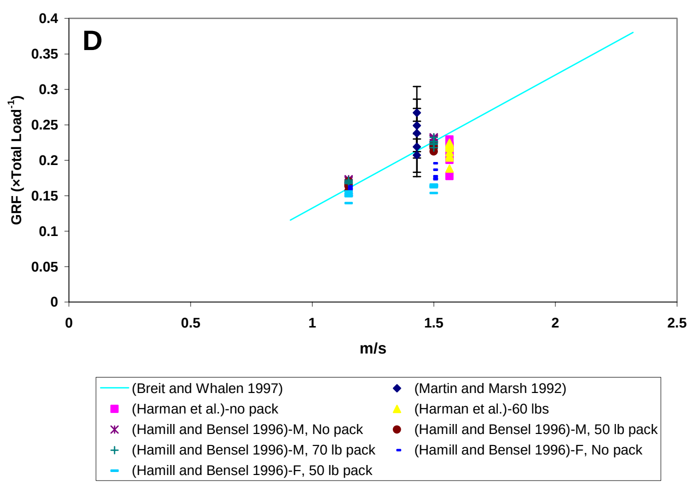


Figure 3-4 First and second peak vertical (A & B), braking (C), and propulsive (D) ground reactions forces (GRF) while walking versus speed from a variety of publications. Reported standard deviations were included where available. Only Breit and Whalen (1997) studied a wide range of speeds and developed a regression equation. Note that gender and external load do not appear to affect normalized GRF values. A wide variety of footwear was used, including boots.



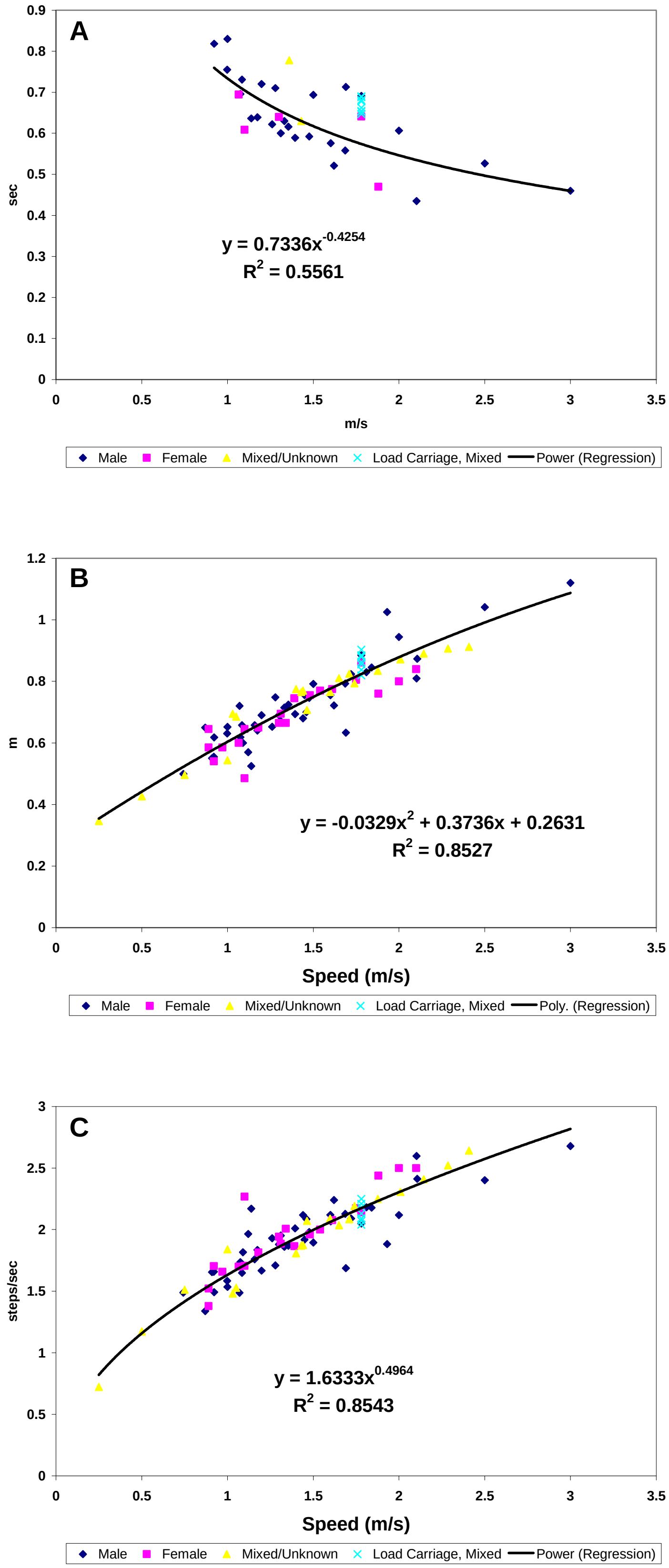


Figure 3-5 Foot contact time (A), step length (B), and step rate (C) while walking versus speed from a variety of publications (Murray et al. 1970; Jansen et al. 1982; Burdett et al. 1983; Chao et al. 1983; Hamill et al. 1984; Martin and Nelson 1986; Nilsson and Thorstensson 1989; Yamasaki et al. 1991; Martin and Marsh 1992; Minetti et al. 1994b; Minetti et al. 1995; Borghese et al. 1996; Donelan and Kram 1997; Hangland and Cimbalo 1997; Kerrigan et al. 1998; White et al. 1998). The results suggest that gender and load have a limited effect on timing measures. Calculated regression line and equation relating timing measures to walking velocity are also shown. A wide variety of footwear was used, including boots.

3.3 Simplified bone stress estimation for Overuse Injury Model 1.0

Because bone is weaker in tension than compression, tension is the most likely cause of stress fracture (see Section 3.1.2). In order to estimate the loading conditions of the bone during marching and running (bone stress), both the magnitude of maximal tensile stress and its variation was estimated. A literature review of *in vivo* bone strain measure on humans was conducted and used to approximate bone stress. Because these values were derived from a limited number of subjects undergoing nonintensive movements, it is likely that these values represented a lower value than that typically seen during basic training. However, we assume that the variation in stress seen during *in vivo* testing is similar to that of the recruit population. Using kinetic and kinematic data from recruits, a mathematical model was used to estimate the more likely magnitude of the tensile stress for an average sized recruit.

3.3.1 Using in vivo bone strain

Six studies were found where tibial bone strains were measured on human subjects while performing various movements such as walking, running, and jumping. In general, compressive, tensile, and shear strains and strain rates were measured. Strain rates were not analyzed in this report. Note that very few subjects were measured (< 10 subjects performed the various movements), most subjects were older and less fit than the typical military recruit (average age ~42 years), and no gender differences were found in this small group. In addition, it is doubtful that the movements were as strenuous as experienced during 12 weeks of basic training.

To determine if a consistent relationship exists between strain and measurable external loads, microstrain was compared to estimated vertical force and regression equations were calculated. For running and walking, vertical force was calculated from the reported velocity and body weight. See Section 3.2. For jumping, it was assumed the vertical ground reaction force was 4.5× body weight.

The results show that strains are variable, depending on the movement and the location of the sensor. In general, microstrain increased with vertical force. See Figure 3-6. However, tensile strains were highly variable and, while dependent on movement (e.g., tensile strain for running was higher than for walking), strains did not change appreciably as vertical force increased for a given movement. There did not appear to be a gender effect

as well. Therefore, it was assumed the tensile strain for each movement (e.g., walking or running) was constant and independent of both external loading conditions or velocity and gender. To convert strain to stress, an elastic modulus of 17.5 GPa was used (Martin 1992). The results can be found in Table 3-3, where the *in vivo* results are compared to values derived from a biomechanical analysis.

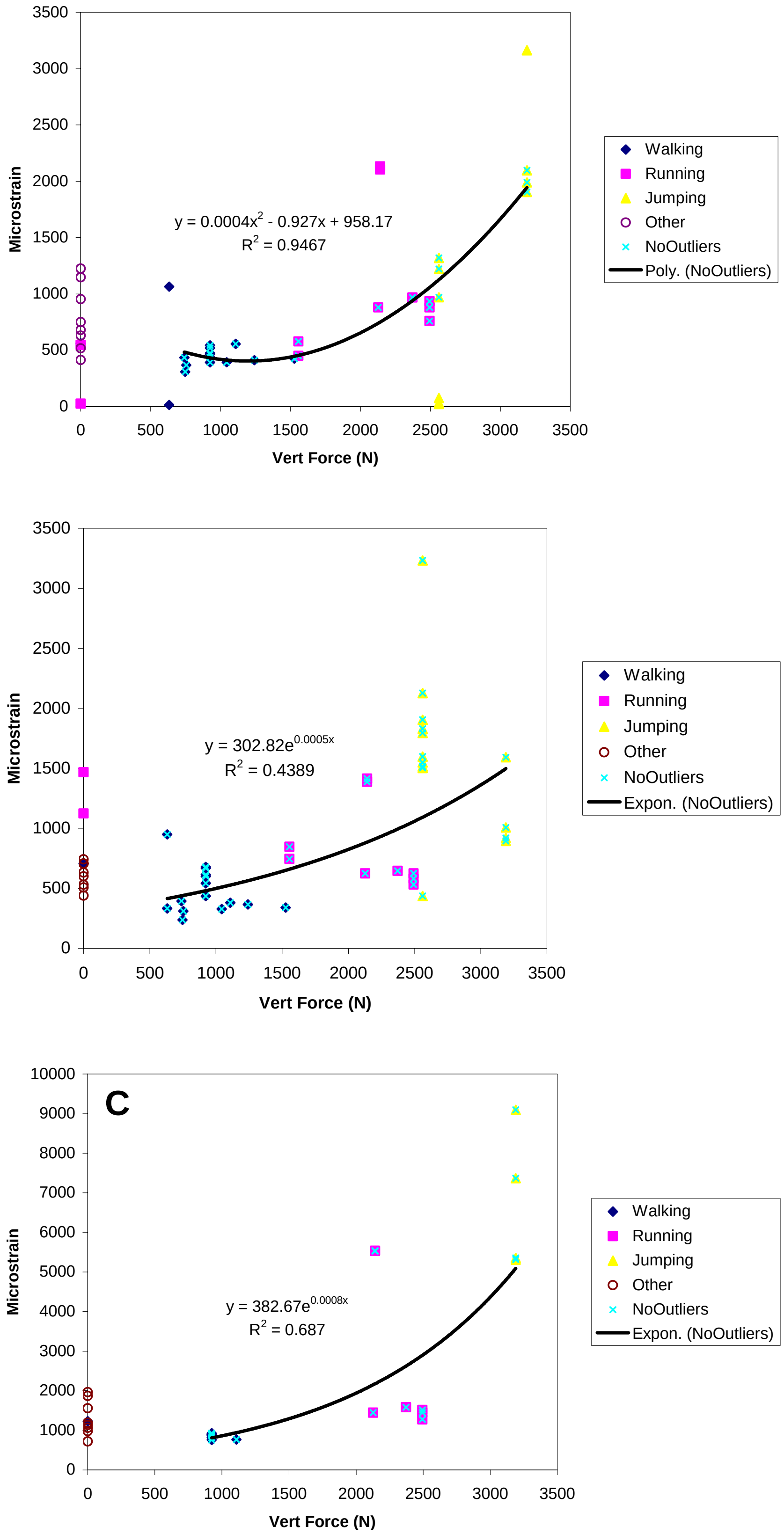


Figure 3-6 Tibial compressive (A), tensile (B), and shear (C) microstrain versus estimated vertical force for various movements. Vertical force was estimated from reported velocities and regression equations developed in Section 3.2. *In vivo* microstrain measures were from various publications (Lanyon et al. 1975; Burr et al. 1996; Milgrom et al. 1996; Ekenman et al. 1998; Milgrom et al. 2000a; Milgrom et al. 2000b). Less than 10 subjects performed the various activities. We were unable to calculate vertical force for those microstrain values shown at zero vertical force. Outliers and values where vertical force could not be estimated were not included in the calculation of the regression equation.

3.3.2 Using a biomechanical model

Being unsure of the appropriateness of the *in vivo* results, a biomechanical analysis based on kinetic and kinematic measures of subjects more representative of the typical recruit was performed. Using an inverse dynamics approach, joint reaction forces and moment of force about the ankle was calculated. These values were translated into bone-on-bone contact and muscle forces using published anthropometry values. Assuming that these forces are the primary loads that cause the tibia to undergo shear and bending, the maximal tensile stress at the distal third was calculated. The typical male recruit was approximately 1.75 m in height and weighed 75 kg. See Chapter 4.

Kinematic and kinetic data for marching and running was obtained from a military boot study (Harman et al.). Four subjects had heights and weights similar to that of a typical recruit. Time traces of ground reaction forces as well as ankle and knee joint locations during walking and running in military boots were used to estimate the joint reaction forces and moment of force. For simplicity, it was assumed that the forced due to the acceleration of the segments was minimal during stance and that medio-lateral contributions were small. Peak values were in agreement with previously published results (e.g., Winter 1990) and were assumed to be reasonable approximations of the forces at the ankle.

Assuming that the primary source of the moment of force was the muscles attached to the Achilles tendon, bone-on-bone shear and compressive forces as well as the muscle-tendon force was calculated. Cadaveric studies suggest that the Achilles tendon moment arm is approximately 3 cm (Hoy et al. 1990) and it was assumed that the muscle force was primarily parallel to the tibia (see Figure 3-7).

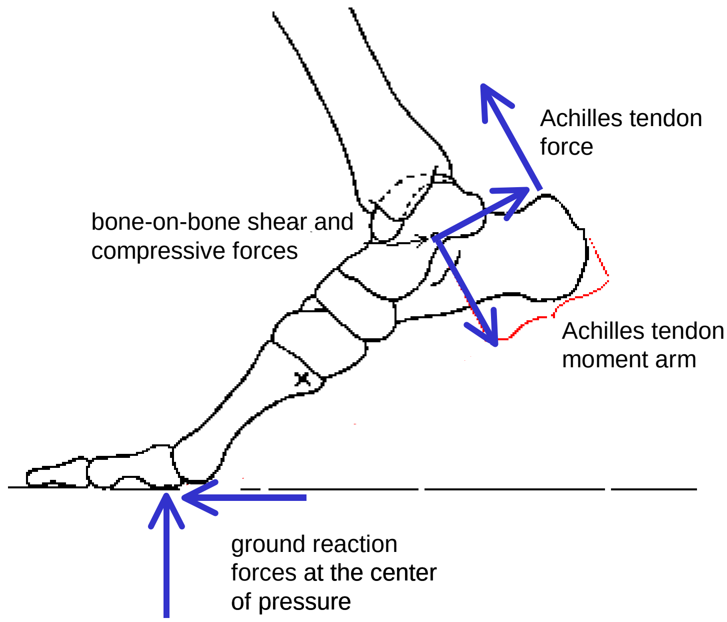


Figure 3-7 Simplified force diagram of the foot-ankle complex. For simplicity, it was assumed that the forces due to segmental accelerations was minimal and the dominant muscle load was applied by the Achilles tendon in a direction parallel to the tibia.

In order to approximate the tensile stress at the location one third from the distal end of the tibia, the cross-sectional area and moment of inertia of the bone was estimated. It was assumed that the primary bending moment occurred about the medio-lateral axis with the highest tensile stress occurring on the anterior surface. A bone scan of the appropriate tibia location was digitized (Crossley et al. 1999) and using the reported medial-lateral and anterior-posterior widths for the typical recruit was used to calculate the cross-sectional area and moment of inertia (see Figure 3-8). Estimated area and moment of inertia about the medial axis was 4.5 cm^2 and 2.6 cm^4, respectively.

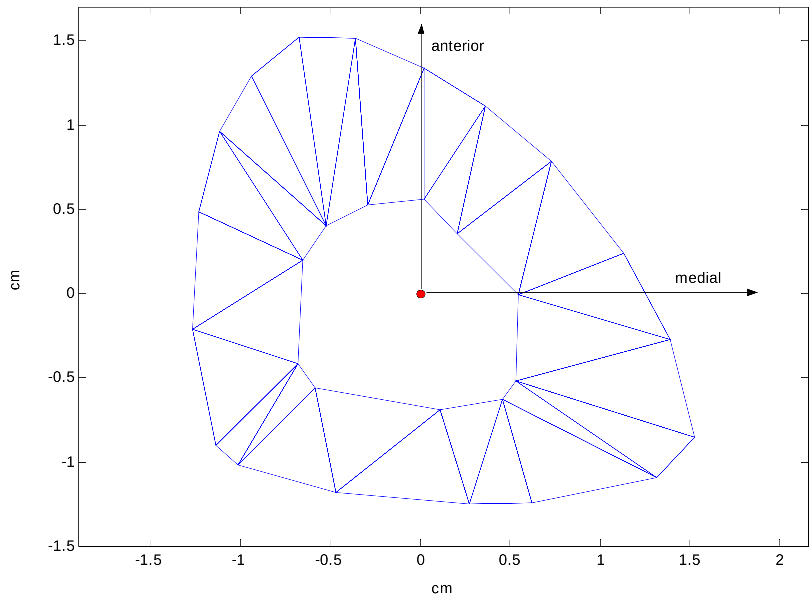


Figure 3-8 Tibial cross-sectional model from the distal third used to estimate area and moment of inertia. Model is based on the bone scan figure depicted in the article by Crossley et al. (1999). Cross-sectional dimensions were adjusted to coincide with the average values given (anterior/posterior width = 2.7 cm, medial/lateral width = 2.3 cm). Estimated area and moment of inertia about the medial axis was 4.5 cm^2 and 2.6 cm^4, respectively.

Tensile stress was calculated by assuming the moment caused by the muscle force as well as the bone-on-bone shear force resulted in pure bending. In addition, knowing the cross-sectional area allowed a compressive stress to be calculated from the bone-on-bone compressive force. As noted by others (e.g., Winter 1990), overall tensile stress was substantially reduced by the elevated compressive forces. Predicted stress estimates can be found in Table 3-3. Note that this calculation is only an estimate for the typical recruit based on a simplified geometry and muscle line of action. Nevertheless, we expect these values to be a reasonable first order approximation. Interestingly, both the model and *in vivo* results suggest that the ratio of walking to running bone stress is 0.54.

Table 3-3 Estimated walk/march and run tensile bone stress in MPa using two different methods (mean ± SD). *In vivo* values were calculated using average strains (see Figure 3-6) and an elastic modulus of 17.5 GPa (Martin 1992). Model calculations were based on kinematic and kinetic measures from four subjects (Harman et al.) and the cross-sectional inertia measures of the distal third of the tibia. Model variation (SD) was assumed to be the same as the *in vivo* measures.

	in vivo estimate	variation ratio	**model** estimate	predicted variation
Walk	8.64 ± 3.40	1.00 ± 0.39	14.6 ±	5.69
Run	15.91 ± 6.45	1.00 ± 0.41	26.9 ±	11.03

Note: both *in vivo* and model results suggest the ratio of walking to running stress is 0.54.

4. Regime Data: U.S. Marine Corp Basic Training

The purpose of this section is to provide an overview of the available data regarding military training, supply quantified training regimes for the Overuse Injury Model, and furnish injury rates for model comparison. Recruit and regime data from U.S. Marine Corp basic training was acquired from the Naval Health Research Center (NHRC). NHRC assistance was provided by Senior Statistician David Ryman. Note that only a small portion of the available measures was utilized in OIM 1.0.

The Marine Corp Recruit Depot (MCRD) training regime is designed to physically and mentally prepare recruits to become U.S. Marines. Because of the extensive physical training, a significant number of acute and overuse injuries are seen. To address this issue, several epidemiological studies involving a large number of recruits have been funded. The data organized here includes background history, anthropometry, bone scan, and injury diagnosis of recruits undergoing U.S. Marine Corp Basic Training. Recruit totals are 1,946 males at MCRD San Diego (1993 & 1995) and 2,981 females at Parris Island (1995-1996). Some of the NHRC publications resulting from this data can be found in Table 4-1, where additional details about the method of data collection and injury correlations can be found.

Table 4-1 Publications based on the MCRD data used for OIM 1.0.

Naval Health Research Center Publications
Almeida, S. A., D. W. Trone, et al. (1999). "Gender differences in musculoskeletal injury rates: a function of symptom reporting?" Med Sci Sports Exerc **31**(12): 1807-12.
Beck, T. J., C. B. Ruff, et al. (1996). "Dual-energy X-ray absorptiometry derived structural geometry for stress fracture prediction in male U.S. Marine Corps recruits." J Bone Miner Res **11**(5): 645-53.
Beck, T. J., C. B. Ruff, et al. (2000). "Stress fracture in military recruits: gender differences in muscle and bone susceptibility factors." Bone **27**(3): 437-44.
Shaffer, R. A., S. K. Brodine, et al. (1999). "Use of simple measures of physical activity to predict stress fractures in young men undergoing a rigorous physical training program." Am J Epidemiol **149**(3): 236-42.
Shaffer, R. A., S. K. Brodine, et al. (1999). "Epidemiology of illness and injury among U.S. Navy and Marine Corps female training populations." Mil Med **164**(1): 17-21.

4.1 Data organization

The form of data acquired from NHRC was either data files (e.g., anthropometry measures) or reports (e.g., training logs). Data files were organized and placed in an Excel workbook and training logs, questionnaires and variable definitions were scanned and converted into Acrobat Reader (.pdf) formatted files.

Detailed descriptions of the datasets can be found in Table 4-2, Table 4-3, and Table 4-4. *However, due to the sensitive nature of the individualized data, no recruit data is included in this report. However, a CD with the training logs, questionnaires and variable definitions (Acrobat files) is attached.* Note that Table 4-4 describes additional injury data and regime descriptions for male recruits at MCRD-San Diego that most likely pertain to training during 1995. However, only thirteen stress fractures were reported, suggesting the records are incomplete. This data was not utilized directly in the Overuse Injury Model. However, missing components of the 1993 MCRD-SD training regime was estimated based on the 1995 measures.

4.1.1 Recruit data

Recruit data was organized into three categories: questionnaire answers, anthropometry (including bone scan measurements) and injury diagnosis. Each recruit was identified by a unique 9-digit number (*Record ID*), which allowed questionnaire, anthropometry and injury to be associated together. Not every recruit completed both the questionnaire and anthropometry measurements nor sustained an injury. However, data compiled can be considered to be randomly sampled from the recruit population. Recruit data was checked for duplicate and erroneous entries by David Ryman from the Institute of Clinical Epidemiology at the Naval Health Research Center.

Male and female recruits (San Diego and Parris Island, respectively) were given different questionnaires. In general, female questionnaire items included menstrual cycle questions whereas male questions focused on diet. Both questionnaires discussed previous injury and exercise patterns. Copies of the questionnaires can be found in *MCRD-XX Questionnaire.pdf.*

Anthropometry measures included weight and height as well as lower extremity distances, circumferences and ranges of motion. A limited number of recruits had bone scans of the tibia, fibula and femur where bone dimensions and mineral content were estimated. Two partial sets of bone scan measurements were acquired: data from NHRC and data obtained directly from the principle investigator, Dr. Thomas J. Beck, Sc.D. Unfortunately, a complete set of bone scan data could not be generated because the NHRC records are incomplete and Dr. Beck’s values have been normalized for height and weight through an unknown process.

Medical visit diagnosis database records contained *Record ID*, dates, injury type, body location and ICD9 injury codes. Unfortunately, database entry was inconsistent and a large portion of the records were incomplete or in error. This was most problematic with dates where day of injury and day of visit were often switched or missing.

4.1.2 Training regime

MCRD basic training was 82 days and most of the physical exercise consisted of marching, running, and various obstacle courses. Training difficulty and duration generally increased with time. Daily training outline plans and direct measurement of exercise distances were used to quantify training. Unfortunately, the training descriptions for Parris Island and San Diego were different, making comparisons between the two regimes difficult.

The MCRD Parris Island 1995 training regime was documented through its Training Outline Plan (*T.P.*, see *MCRD-PI Training Data.pdf*). The *T.P.* documented each day's main activities, time allotted, and, in some cases, distances traveled. Activity details such as exact times and distances were not available.

NHRC measured training distances for the MCRD San Diego 1995 group, including movement, march/hike and physical training miles as well as load carried (see *MCRD-SD Training Data.pdf*). MCRD San Diego 1993 training logs consisted of daily physical training activities and times but did not document Close Order Drill exercises.

Table 4-2 Final file names and contents descriptions for organized 1995-96 Parris Island female data. (Only .pdf files are included in this report.)

Parris Island Female Data 1995-96 (& 1999 Questionnaire)

MCRD-PI 1995 OIM Data.xls (Excel Workbook)	OIM 1.0 input data, including quantified regime (day, run/walk, velocity, number of steps, external load) & recruit data with *Record ID* removed (body mass, stress fracture, day of fracture).
MCRD-PI Anthro.pdf (Adobe Acrobat)	Demographics and anthropometrics data sheet, anthropometric protocol, and additional anthropometric variable definitions.
MCRD-PI Questionnaire.pdf (Adobe Acrobat)	Questionnaire (including variable names), questionnaire Code Book, and additional questionnaire variable definitions.
MCRD-PI Training Data.pdf (Adobe Acrobat)	Platoon start dates, Training Outline Plans (Late April-October & November-Mid April), Training Abbreviations Key, and movement distances.
MCRD-PI 1995 Data.xls (Excel Workbook)	
FileDescription	Name and brief description of all the worksheets in the workbook. Also includes names of .pdf files where additional information can be found.
PI956InjuryData	Injury data sorted by *Record ID*. ICD9 code, estimated injury day and injury location are compiled. Follow-up visits for the same injury have been removed. Simplified injury location and injury type codes are also defined. Injury type code is based on the reported ICD9 code. However, only ICD9 codes relating to stress fractures have been noted.
PIDIAG	Original medical diagnosis database file of all visits for medical treatment, including repeat visits for the same injury. Database contains *Record ID*, Platoon Number, date of visit and injury, ICD9 codes and diagnosis. Injuries were also classified as stress fracture, acute, overuse and dermal. Note that data entry is inconsistent with visit day and day of onset often reversed and other anomalies.
PlatoonStartDate	Start date by platoon number. Note that platoon number is known only for injured recruits (*PIDIAG*).
PI95TrainDist	Estimated training regime and loading profile based on the April-October Training Outline Plan.
PI956QST	Questionnaire answers, including self-reported height and weight (*SDHT* and *SDWT*) sorted by *Record ID*. Stress fracture and overuse injury are also noted. A copy of the questionnaire is saved in *MCRD-PI Questionnaire.pdf*.
PI956ANT	Anthropometry and demographics sorted by *Record ID*. Stress fracture and overuse injury also noted.
PI956SCA	NHRC bone scan data sorted by *Record ID*. Stress fracture and overuse injury also noted. Where known, measurement units are noted. Bone measure definitions can be found in Beck (1996 & 2000).
FEMLSCAN	Dr. Beck bone scan data sorted by *Record ID*. Worksheet contains additional measures not included in *PI956SCA* but was normalized for height and weight through an unknown process. Thus, measurement units are not known.
PI99QST	Additional set of questionnaire answers from 1999. The regime in 1999 included intense “Crucible” training. No additional information is known about this group or the regime.

Table 4-3 Final file names and contents descriptions for organized 1993 San Diego male data. (Only .pdf files are included in this report.)

San Diego Male Data 1993

MCRD-SD 1993 OIM Data.xls (Excel Workbook)	OIM 1.0 input data, including quantified regime (day, run/walk, velocity, number of steps, external load) & recruit data with *Record ID* removed (body mass, stress fracture, day of fracture).
MCRD-SD Anthro.pdf (Adobe Acrobat)	Demographics and anthropometrics data sheet, anthropometric protocol, and additional anthropometric variable definitions.
MCRD-SD Questionnaire.pdf (Adobe Acrobat)	Questionnaire Code Book (including variable names) and questionnaire with first page missing.
MCRD-SD Training Data.pdf (Adobe Acrobat)	Training Schedule (alpha and bravo) circa 1993, 1995 training distances, measured training distances and loads, Training Abbreviations Key, and platoon start dates.
MCRD-SD 1993 Data.xls (Excel Workbook)	
FileDescription	Name and brief description of all the worksheets in the workbook. Also includes names of .pdf files where additional information can be found.
MCRD93InjuryData	Injury data sorted by Record ID. ICD9 code, estimated injury day and injury location are compiled. Follow-up visits for the same injury have been removed. Simplified injury location and injury type codes are also defined. Injury type code is based on the reported ICD9 code. However, only ICD9 codes relating to stress fractures have been noted.
PlatoonStartDate93	Start date by platoon number. Note that platoon number is known only for injured recruits (MCRDCOM).
MCRD93TrainDist	Estimated training regime and loading profile based on the MCRD Info training schedule.
MCRD93TrainDistModified	Estimated training regime and loading profile based on the MCRD Info training schedule and modified based on additional movement miles and loads from MCRD-SD 1995 data.
SDMCRDQS	Questionnaire answers sorted by Record ID. Stress fracture and overuse injury are also noted as well as initial 3 mile run time for some recruits. A copy of the questionnaire is saved in MCRD-SD Questionnaire.pdf.
SDMANTH	Anthropometry and demographics sorted by Record ID. Stress fracture and overuse injury also noted.
MCRDCOM	Stress fracture injuries sorted by Record ID. Includes dates, injury location, result, and platoon number. Does not contain diagnoses for other injuries.
MALESCAN	Dr. Beck bone scan data sorted by Record ID. Measures were normalized for height and weight through an unknown process. Measurement units are not known.

Table 4-4 Final file names and contents descriptions for organized 1995 San Diego male data. (Files is not included in this report.)

San Diego Male Data 1995	
MCRD-SD 1995 Data.xls (Excel Workbook)	
FileDescription	Name and brief description of all the worksheets in the workbook. Also includes names of .pdf files where additional information can be found.
MCRDDIAG95	Original medical diagnosis database file of visits for medical treatment, including repeat visits for the same injury. Database contains Record ID, Platoon Number, date of visit and injury, ICD9 codes and diagnosis. Injuries were also classified as stress fracture, acute, overuse and dermal. Records may not be complete.
PlatoonStartDate95	Start date by platoon number. Note that platoon number is known only for injured recruits (MCRDDIAG95).
MCRD95TrainDist	Estimated training regime and loading profile based on the MCRD Info training schedule.
SDMCRDDX	An additional medical diagnosis database file with incorrectly entered dates (records are not from 1993). Actual dates unknown.

4.2 Data processing: Overuse Injury Model dataset

As described in Chapter 1, OIM 1.0 requires loading history for model input and stress fracture history for model output comparison; both of these quantities were obtained from the NHRC datasets. In general, the female dataset was larger, documented more stress fractures, and had more complete training regime documentation.

4.2.1 Quantification of training regime

Loading history was specified by load magnitude and number of loads per day. A literature review was used to estimate the magnitude of bone stress during walking/marching and running (see Section 3.3). In this initial model, it was assumed that the effect of external loads such as pack weight on bone stress was minimal.

Number of loads per day was determined by estimating the number of steps taken. For each day, distance traveled and velocity were estimated. It was assumed that all walking and marching was performed at 1.56 m/s (see Novacheck 1998; Trank et al. 2001) and that missing running velocities were similar to known run values. Using the regression equations developed from a review of the literature (see Section 3.2), the number of steps per day for marching/walking and running was estimated (Figure 4-1 and Figure 4-2). Differences in training for individuals and platoon was not available and it was assumed that all recruits underwent the same basic training regime. In addition, it was assumed that the male training regime did not appreciably change between 1993 and 1995 (except where noted on the training logs) and, where necessary, 1995 Close Order Drill and other values were used for 1993.

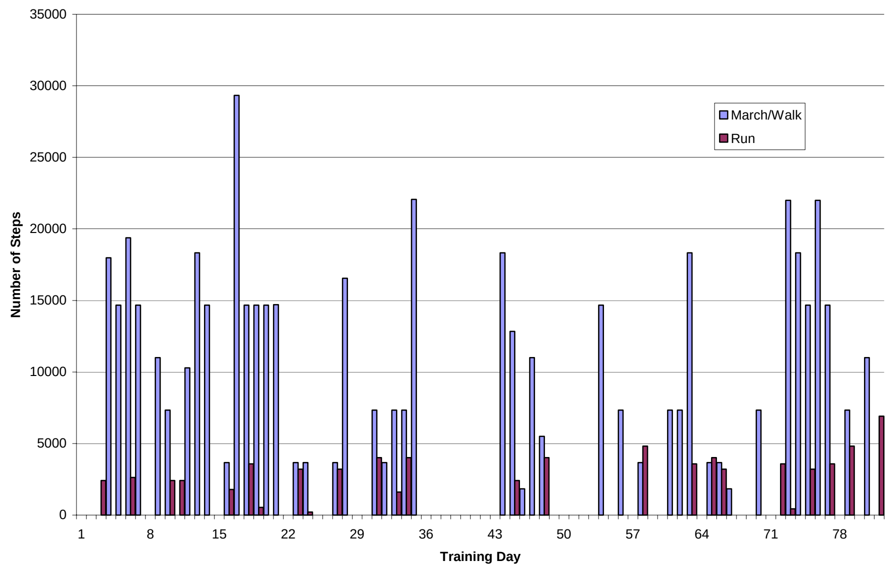


Figure 4-1 Estimated number of walking/marching and running steps taken during each day of basic training for females at Parris Island 1995-96. Number of steps were estimated from training outline plans and regression equations derived from the literature (see Section 3.2).

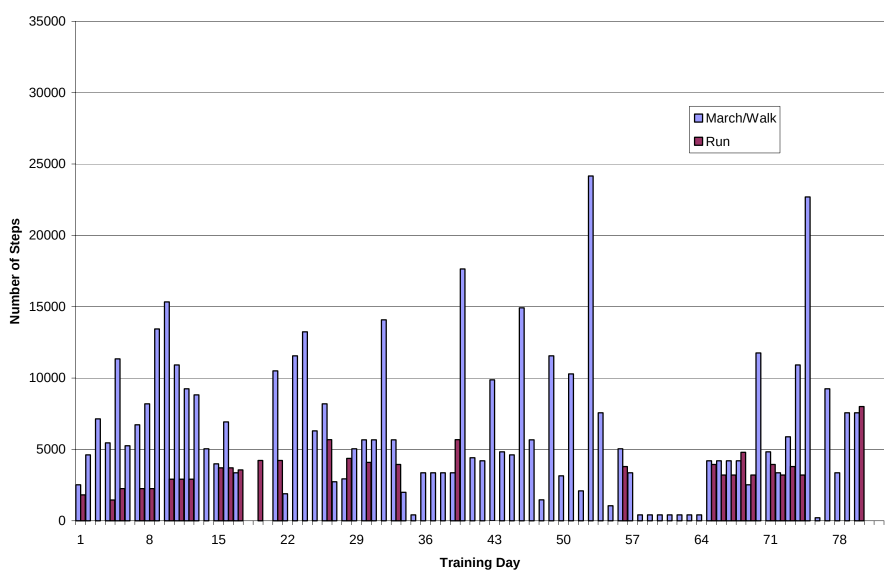


Figure 4-2 Estimated number of walking/marching and running steps taken during each day of basic training for males at San Diego 1993. Number of steps were estimated from training outline plans and regression equations derived from the literature (see Section 3.2).

4.2.2 Organization of stress fracture data

Data organization consisted of grouping injury type, onset day, and body location for each recruit. Determination of onset day was hampered by inconsistent database entry and it was assumed that the true onset day was the earliest reported time of injury for repeated

visits for the same injury. After processing, a worksheet containing each recruit's injuries, described by an ICD9 injury code, estimated onset day, and injury location was created. On each training day, stress fractures were then summed regardless of fracture location to give the total number of stress fractures per day (Figure 4-3 and Figure 4-4). The overall rate of stress fracture was approximately 4.5% for female and 3.6% for male recruits.

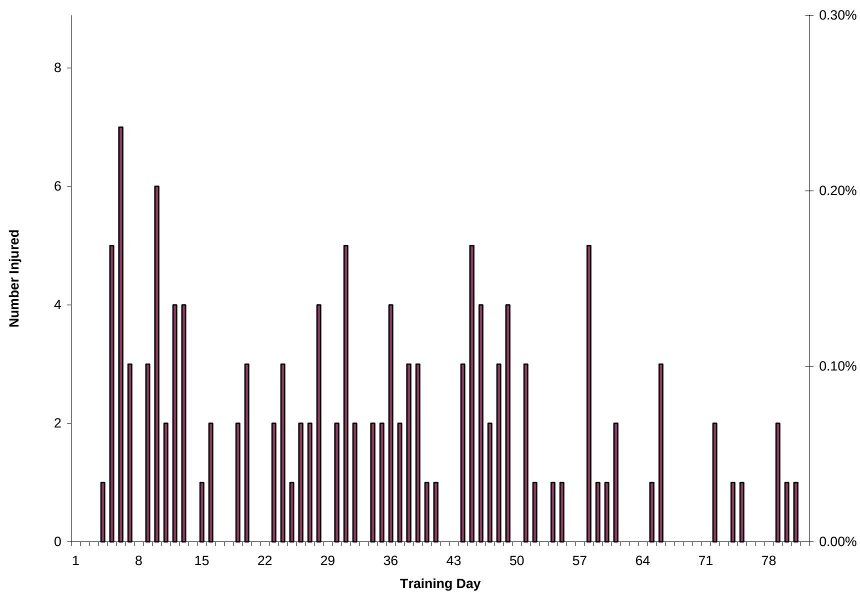


Figure 4-3 Reported number of stress fractures during each day of basic training for females followed at Parris Island 1995-96. Percent injured is based on 2,963 recruits.

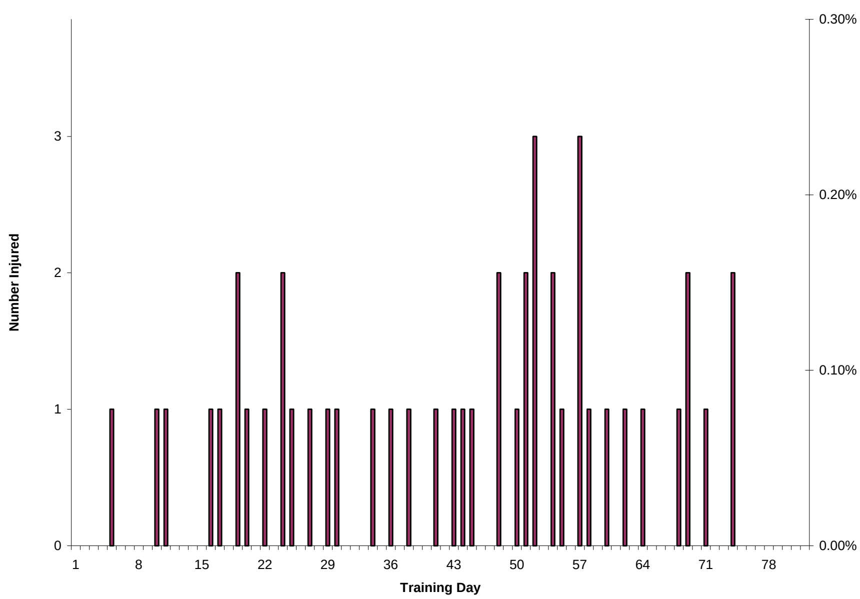


Figure 4-4 Reported number of stress fractures during each day of basic training for males followed at San Diego 1993. Percent injured is based on 1,286 recruits.

5. Overuse Injury Model 1.0

5.1 Theoretical bone model overview

Several different bone models have been proposed (Table 5-1) using a variety of methods including regression equations developed for nonbiomaterials, neural networks, and statistical analyses. In addition to modeling fatigue damage, several studies have incorporated bone repair functions to account for both modeling and remodeling. Usually, bone damage is assumed to be proportional to the number of loads and the load (strain or stress) raised to a power:

$$D = k \cdot N \cdot \Delta\sigma^{q} \qquad 1.1$$

where D is a damage measure such as crack length or change in elastic modulus, k is a proportionality constant, N is the number of load cycles, $\Delta\sigma$ is the load level, and q is the power constant. Our preliminary experiments (see Shen et al. 2000) suggested that the results from this type of model may be unstable, being highly dependent on the value of the exponent. In addition, the complex microstructure of bone (i.e., secondary osteons) suggest that damage rate may depend on the level of micro- and macro-damage, something that is not easily controlled for in Equation 1.1. Also, while the process of damage repair through the propagation of BMU's is well understood, how it is controlled and the effect on damage level is not. Thus, several different algorithms have been proposed of varying complexity to model the repair process of bone. Almost all models assume an undetermined feedback system that allows BMU's to concentrate on damaged bone. Thus, some models are complex and unstable, making them difficult to implement.

Table 5-1 Some bone damage models found in the literature.

Mathematical Bone Damage Models
Griffin, L. V., J. C. Gibeling, et al. (1997). "Model of flexural fatigue damage accumulation for cortical bone." J Orthop Res **15**(4): 607-14.
Hasan, M. S., A. Faruque and D. B. Burr (1997). "Application of artificial neural network for micro-crack and damage evaluation of bone." Biomed Sci Instrum **33**: 382-7.
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The bone fracture model chosen for the initial overuse injury model was based on "Bone Maintenance and Remodeling: A Control System Based on Fatigue Damage," a theory proposed by Taylor (1997). Two important characteristics of this model are 1) its inclusion of micro- and macro-crack behavior and 2) its inherent stability to loading conditions without the need of an intelligent system to repair bone damage. A model of microcrack growth based on bone fatigue characteristics is combined with a simple constant rate of repair. The system that results is inherently stable with a "lazy zone" for crack lengths where crack growth due to cycling stress is countered by the remodeling rate.

5.1.1 Equation of microcrack growth

An important but often overlooked characteristic of materials is that crack growth rate (change in length per loading cycle) has been shown to slow as microstructure features such as grain boundaries in metals and cement lines of bone impede progress. However, once crack length is greater than the microstructure features, growth rate accelerates. See Figure 5-1. Taylor (1997) uses the following equation to describe this behavior for compact bone:

$$\mathrm{d}a/\mathrm{d}N = C\left(\Delta K - \Delta K_{\mathrm{th}}\right)^{\mathrm{n}} + C'\Delta K^{\mathrm{n}'}\left[(d-a)/d\right]^{\mathrm{m}} \qquad 1.2$$

where a (mm) is crack length, N is load cycle, and d (μm) is the average spacing between microstructural features that are barriers to crack growth such as cement lines. The first

term describes long crack behaviour ($a > d$), and the second term is used for short cracks. The parameter ΔK represents the cyclic stress intensity, which is related to the cyclic stress ($\Delta\sigma$) and the crack length by

$$\Delta K = F\Delta\sigma(\pi a)^{1/2} \tag{1.3}$$

where F is a constant dependent on crack geometry, specimen and load type. The parameters C, C', n, n', m, and ΔK_{th} are constants whose values have been previously estimated from fatigue data on dead bone (see Table 5-2) and the units of da/dN are in millimeters per cycle. The parameter values were primarily obtained with the use of a simplified two-dimensional geometry where a crack originates at the surface and grows toward and through a single barrier.

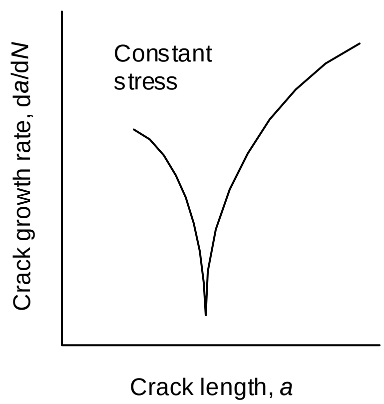

Figure 5-1 Typical crack growth rate versus crack length in a material with microstructural barriers. The growth rate is impeded as it encounters barriers such as cement lines in bone and accelerates rapidly as crack length becomes large (Taylor 1997).

Table 5-2 Overuse Injury Model 1.0 bone parameters (Taylor 1997).

Parameter	Description	Value
C	Rate constant (long cracks)	1.3×10^{-5}
C'	Rate constant (short cracks)	1.3×10^{-2}
n and n'	Stress exponents	4.5
m	Barrier sensitivity	5
d	Microstructure size	100 µm
F	Cyclic stress intensity constant	1.12
ΔK_{th}	Baseline stress intensity	0.2 MPa(m)$^{1/2}$

5.1.2 Constant bone repair

Repair can be modeled as negative growth or a reduction in crack length, which can be represented by a horizontal line on a growth rate versus length graph for constant

repair. Taylor (1997) proposes that under normal loading conditions (i.e., repair is capable of keeping up with damage) the growth rate due to stress intersects the repair rate at two points. See Figure 5-2. Point A is called an *attractor* because crack lengths near this length will always arrive at A. At crack lengths smaller than specified by A, growth is faster than repair and the crack lengthens. At lengths greater (but less than R), repair is faster, which reduces crack length. Point R, in contrast, is a *repellor* and is unstable as crack lengths will always move away from this point to either Point A or towards fracture.

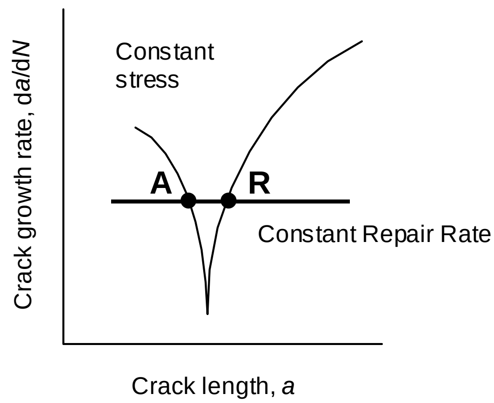

Figure 5-2 Effect of a constant repair rate on crack growth. At points A and R, growth and repair are equal. However, only Point A is stable (attractor). With any deviations in stress, at Point R (repellor) crack length will either be reduced to Point A or lengthen and fracture (Taylor 1997).

The result of this model is that a constant crack length can be automatically achieved and is inherently stable without the need of complex feed back systems, provided that the stresses are within a range that allows repair. Another feature of this model is that fracture occurs relatively quickly if the crack length becomes greater than specified by Point R, where the constant repair rate quickly becomes substantially slower than crack growth.

5.2 Methods

5.2.1 Input variables

In order to simulate a group's basic training experience and correlate it to stress fractures, bone parameters, training regime and recruit characteristics were quantified. A concerted effort was made to use realistic parameters and values. In addition, it was assumed that certain model parameters as well as the training regime were the same for all recruits. However, for some variables a lognormal distribution was used to avoid negative values (an impossibility) and to allow for a small number of extremely high values,

representing recruits who are near injury from previous undocumented training and/or unaccustomed to the sudden increase in workload. All parameter mean values were chosen to be within currently accepted values.

Bone parameters

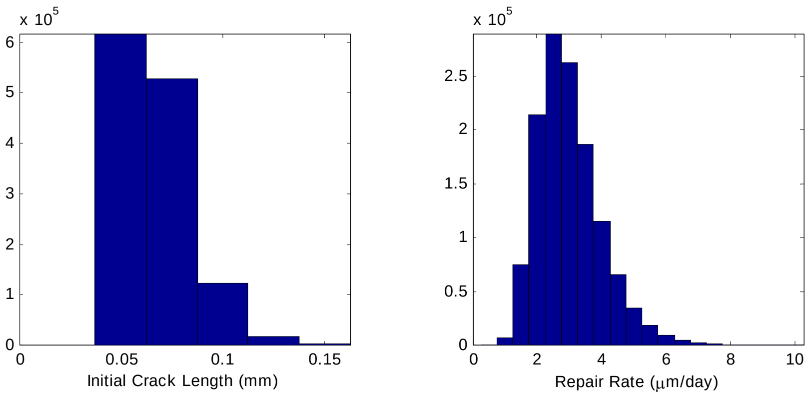

Figure 5-3 Lognormal distribution of initial crack length and repair rate used in Overuse Injury Model 1.0. Average values were taken from Taylor (1997).

Static model parameters were estimated by Taylor (1997) and can be found in Table 5-2. Initial crack length and repair rate were assumed to be distributed (Table 5-3). Values were taken from Taylor (1997) where his literature review suggested that observed crack lengths could average 66±16 µm for bone and that repair rates of about 3 µm/day based on basic multicellular units movement rates can be expected. Repair rate standard deviation was assumed to be 1 µm/day.

Table 5-3 Overuse Injury Model 1.0 bone parameters whose values were randomly varied according to a lognormal distribution. Values are presented as mean±SD. Average values were taken from Taylor (1997).

Variable	Value
Initial crack length	66±16 µm
Repair rate	3±1 µm/day

Training regime

From the training regime data acquired, daily number of steps running and walking/marching were estimated for the Parris Island 1995-96 and San Diego 1993 databases. See Section 4.2 for methodology. Copies of the training regime input files can be found in *MCRD-PI 1995 OIM Data.xls* and *MCRD-SD 1993 OIM Data.xls*.

Recruit bone stress

Assuming that the stress levels measured at the distal third of the tibia (a common stress fracture site) are representative of levels at other injury sites, possible upper and lower limits for bone stress during walking and running was previously estimated from modeling and *in vivo* measures. In addition, it was assumed that the variation (distribution) of *in vivo* measures is representative of the population variation, regardless of stress magnitude. (See Table 3-3 for variation ratios as well as estimated stress ranges.) As mentioned earlier, we anticipate that microcrack propagation, with regions of weakness and stress concentration, to have higher stress levels than indicated by *in vivo* strain measures during nonintensive movements (e.g., Taylor and Prendergast 1997). In addition, both *in vivo* and modeling estimates suggest that the stress due to walking is 0.54 of running. Lacking any female bone stress estimates, we assumed that bone stress was similar between genders. For this analysis, bone stress distributions were chosen to reasonably approximate the injury rate observed for both male and female datasets.

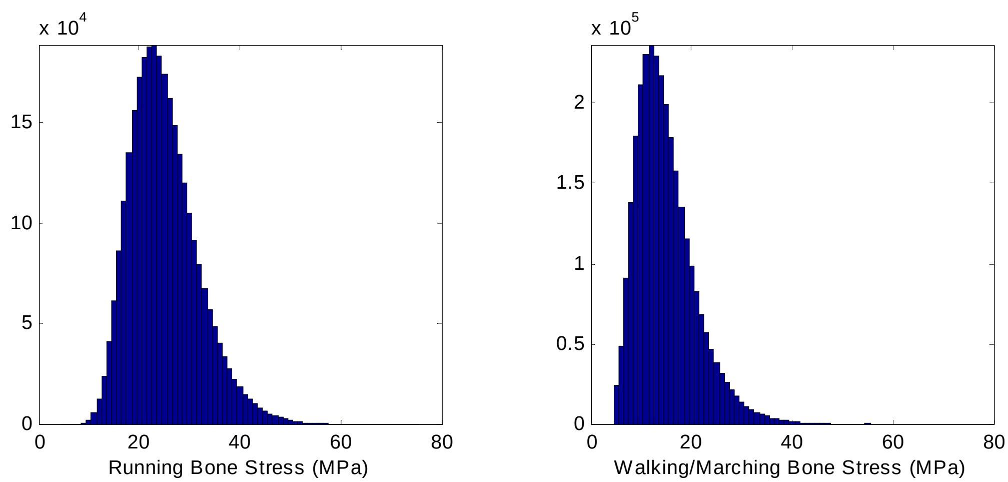

Figure 5-4 Example of the log normal distribution for bone stress due to running and walking/marching used in OIM 1.0 for the Parris Island and San Diego simulation. Mean and standard deviation values were chosen to give a reasonable approximation of the observed fracture rate for both datasets.

5.2.2 Implementation of OIM 1.0 in MatLab and comparison to observed fracture rates

The Overuse Injury Model was implemented in MatLab 6.5 using a nonlinear iteration scheme to solve Equation 1.2, a first order differential equation. Stress fracture was assumed to occur if crack length was greater than 5 mm. Using the quantified regimes

detailed in Section 4.2, the model parameters listed in Table 5-2, and individual recruit parameters that were randomly sampled from the lognormal distribution, the cumulative injury rate for a large number of different simulations was calculated. Both male and female initial crack length and repair rate were assumed to be the same (Table 5-3). Bone stress distributions were specified through the average running bone stress. The distribution about the mean and walking bone stress was assumed to be the ratios listed in Table 3-3. Values were chosen to reasonable approximate the injury rate observed (Table 5-4).

Table 5-4 Overuse Injury Model 1.0 bone stress variables whose values were randomly varied according to a lognormal distribution. Values are presented as mean±SD. Values were within the range derived from multiple studies, as described in Section 3.3. Bone stress distributions were chosen to reasonably approximate the injury rate observed.

Variable		Value
Male:	Running	20.8±8.4 MPa
	Walking	11.2±4.4 MPa
Female:	Running	25.4±10.3 MPa
	Walking	13.7±5.4 MPa

A Monte Carlo simulation was implemented to determine the stress fracture rate. To allow a direct comparison of the model to observed fracture rates, the number of simulated recruits was set to equal the number of actual recruits whose stress fracture history was followed. One thousand randomly selected groups of recruits were simulated and daily cumulative injury rate was calculated. For each day, cumulative injury mean and range of the middle 90% of the predicted values (i.e., 900 of the 1000 simulations nearest the mean) were calculated.

Actual injury rate for all stress fractures was calculated from two of the recruit databases described in Chapter 4 (Parris Island 1995-96 and San Diego 1993). It was assumed that the model represented the fracture characteristics of all the various injury locations which comprised the actual fractures found. Note that some observed fracture cases occurred prior to any reported training, suggesting that stress fractures sustained during this time were not due to the regime. Therefore, these initial stress fracture cases were not included in the reported cumulative total for comparison with the model results.

5.3 Results

5.3.1 Simulation of San Diego male data 1993

For the U.S. Marine Corp male, 1,286 recruits who trained in San Diego during 1993 was simulated. Using nonintensive bone stress estimates, the model predicted a nominal number of stress fractures. However, with properly chosen bone stresses, OIM 1.0 predicted an overall stress fracture rate of 3.6% with 90% of the values falling between 4.4% and 2.7%, in agreement with the observed overall fracture rate (Figure 5-5). The majority of the observed results were within 90% of the range predicted by OIM 1.0. However, the overall trend did not appear to be clearly captured.

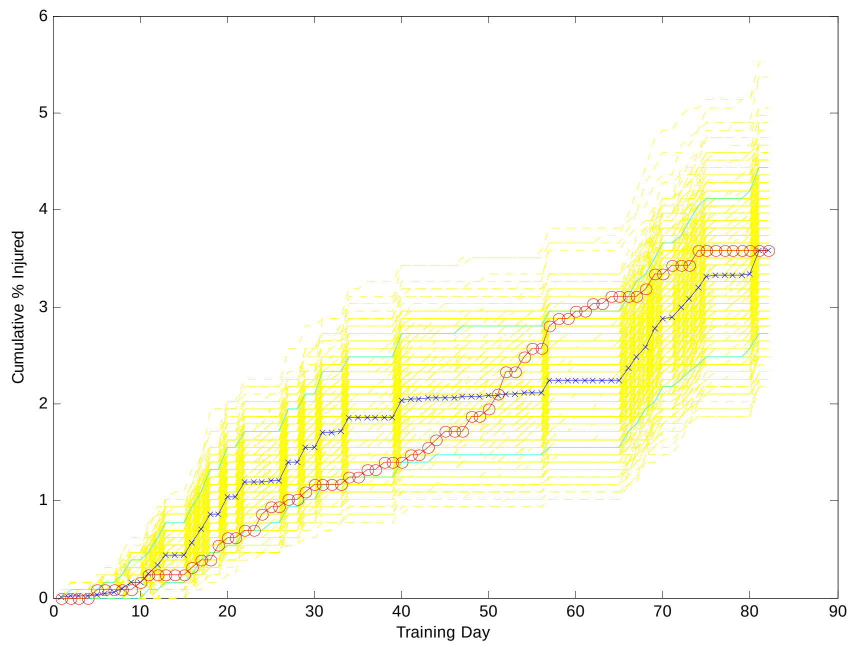

Figure 5-5 Cumulative injury rate as a percent of the number of recruits (1,286) during basic training for males at San Diego 1993 using stresses that gave reasonable results for the dataset. Yellow dashed lines represent one thousand separate simulations, blue line with crosses represents the simulation average and the red line with circles represents the observed injury rates. The light blue lines mark the boundary where 90% of the simulation results lie between.

5.3.2 Simulation of Parris Island female data 1995-96

For the U.S. Marine Corp female, regime and fracture data from 2,963 recruits who trained on Parris Island during 1995-96 was simulated. With this regime, OIM 1.0 predicted an overall stress fracture rate average of 4.5% with 90% of the values falling between 3.9% and 5.1%. Observed overall fracture rate was also 4.5% (Figure 5-6). In addition, the change in cumulative fracture number as the training regime progressed was

in good agreement between the OIM 1.0 simulation and the observed data with almost all observed values falling within the predicted 90% range. This suggested that with the proper parameters, the model is able to predict the overall trend of the injury progression.

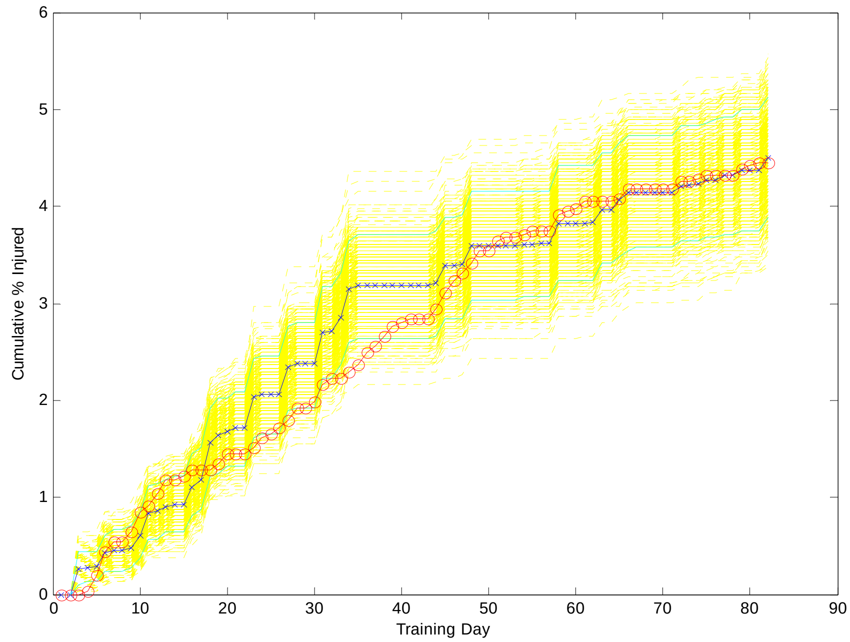

Figure 5-6 Cumulative injury rate as a percent of the number of recruits (2,963) during basic training for females at Parris Island 1995-96 using stresses chosen to closely approximate the observed injury rate. Yellow dashed lines represent one thousand separate simulations, blue line with crosses represents the simulation average and the red line with circles represents the observed injury rates. The light blue lines mark the boundary where 90% of the simulation results lie between.

5.4 Discussion

OIM 1.0, a stress fracture prediction algorithm, is based on a theoretical model developed by Taylor (1997) and utilizes realistic parameters and values. Thus, it may be capable of capturing the overall stress fracture trend in basic military training. For U.S. Marine Corp basic training, normal stress levels were insufficient to cause a substantial number of stress fractures, a characteristic that is in agreement with the stress fracture paradox. However, the observed fracture rate for both male and female recruits was generally within the variation of 90% of the OIM 1.0 simulations, when using an elevated parameter value.

For females, the model and observed results seem to be in better agreement than for the male group (see Figure 5-6). One possible reason is that the female dataset was approximately 50% larger, with a corresponding increase in stress fractures. This likely

minimized the daily fluctuations in reported cases during the 12 weeks of training. Also, quantification of the training regime was likely more accurate as the male regime was composed of estimates from two different years. We limit the remaining discussion to the more complete female dataset.

For females, Service Week occurred during from Day 37 through 43 and stress fractures were reported despite the complete lack of physical activities scheduled. Because the model is based on the loading regime, no stress fractures were predicted for this week. However, observed fracture rate is dependent on an accurate assessment of day of fracture. The most likely explanation is that recruits, realizing that Service Week was approaching, delayed seeking medical attention until this time. Not failing basic training is a strong incentive for a recruit to not seek medical attention as soon as possible (Almeida et al. 1999a) and day of fracture may not be accurate. Thus, there may be a substantial “delay” in the reporting of stress fractures that can confound the model results.

Day 72 to 77 saw a large increase in training distance (Figure 4-1) for females but a limited change in the number of observed injuries, a feature that OIM 1.0 was able to duplicate. This was a direct result of the model repairing noninjured recruit’s bones during the middle of basic training, where training distances were reduced. We further hypothesize that incorporating bone modeling into OIM 1.0 will further improve the model by allowing geometry adaptations to the higher loading stresses.

5.4.1 Areas for model development

Currently, OIM 1.0 does not appear to be a substantial improvement over a direct correlation between training distance and stress fracture injury, especially for the male dataset. While studies directly relating training distances to injuries have had limited success (see Section 3.1.2), there is potential for OIM 1.0 to improve.

We note that a limited number of regimes has been used, that the parameters (and their distributions) are only estimates, and that the model in its present form is only an approximation of crack length propagation due to cyclic stresses *in vivo*. Because of these factors, the feasibility of OIM 1.0 to improve its ability to predict fracture rate for additional training regimes is unknown. In addition, the final stress that causes fracture of a weakened bone is likely a random event such as stumbling, something that cannot be accounted for in the current version of the model. However, the model is based on known

crack growth characteristics and the close agreement between the OIM 1.0 and the observed fracture rate for one of the initial sets of training regimes is very encouraging.

A key component of OIM 1.0 is the lognormal distribution of four parameters: crack length, repair rate, bone stress from running, and bone stress from walking/marching. Unfortunately, it is not feasible to easily determine the true distributions of these parameters from recruits as this is not yet technologically or financially practical. Like all biological (and random) systems, there is some variability that influences results and a lognormal distribution seems to be a reasonable first-order approximation as comparison of the model to observed fracture rates supports the use of a distribution.

One reason the feasibility of OIM 1.0 to predict stress fracture for various regimes was inconclusive was because the available data collected used different techniques. The Parris Island regime was quantified from training plans, which detailed all scheduled events for each day but did not indicate whether all platoons followed the schedule, whereas distances traveled for the San Diego recruits was measured directly but may not have included all events. Thus, it is difficult to compare the male and female model results. However, the female data appears to follow the overall cumulative trend (Figure 5-6).

There are several modifications that may lead to improved results. First, bone modeling (adaptation of bone geometry to reduce stress) is a known response to stress changes and has not been included in OIM 1.0. Such a feature may explain why OIM 1.0 is in disagreement with observed stress fracture rates, predicting an increase in stress fractures during the middle of training—in actuality rapid bone modeling (woven bone) may have sufficiently lowered stress to reduce the number of observed injuries during this time (Figure 5-6). Second, it may be possible to improve the parameter distribution estimation. While it is unlikely that determining the distribution for initial crack length and repair rate will be feasible, it may be possible to more accurately determine an individual's bone stress though the combined use of bone scans to determine cross-sectional area and force sensors to determine ground reaction forces. Third, the static model parameters appear to be an excellent approximation but adjustments may improve results and optimization methods may help improve the model by searching for the best set of parameters. Most importantly, additional sets of stress fracture cases with entirely new training regimes quantified in a consistent manner would help verify the predictability of the model and help guide in additional model developments.

This is the first known model based on observed bone material properties and fracture characteristics to estimate stress fracture rate during basic training. Previous studies have quantified training regimes, noting or hypothesizing that correlations exist between training and injury (e.g., Giladi et al. 1985; Finestone et al. 1991; Jones et al. 1994; Levenston et al. 1994; Canham et al. 1996; McCreadie and Goldstein 2000). However, none of these studies based their results on the known properties of fatiguing bone. Because of this, the effect of varying training regimes (and bone stresses) is unknown, making the correlations of limited use. OIM 1.0, on the other hand, has the potential of predicting stress fracture rates for novel training regimes.

6. Conclusions

This report documents the development of Overuse Injury Model 1.0, a model designed to analyze stress fractures for different training regimes using realistic data and concepts from various resources. Training regime and injury data was acquired from NHRC, allowing an estimation of the loading conditions on the bones and injury rates for model comparison. A literature review enabled the development of regression equations to convert training regime measures to ground reaction forces and these forces to bone stress. Using a published bone model, stress fractures were predicted from the bone stress history.

OIM 1.0 was not notably better than a direct comparison to training distance. Like most initial models, however, there are several areas for improvement that can be recommended. In general, additional model development will largely depend on the quality of the input data and many of the recommendations are designed to address this issue:

- Sensors to more accurately measure ground reaction forces on recruits
- Analyze additional training regimes
- More accurate medical documentation
- Update OIM 1.0 to include bone modeling (adaptation)
- Explore value of additional recruit data such as anthropometry & initial fitness level
- Determine OIM parameters with optimization techniques

Standardization of the training quantification likely will have the greatest benefit, allowing a comparison of different regimes and/or load carriage. Thus, sensors to directly measure loading conditions or other more in depth measurement systems would be valuable. In addition, more accurate injury record keeping would help model calibration. Two additional datasets have been found that may contain enough information for the model and the principal investigators have been contacted. The project expects to acquire the datasets in the next year. With more accurate inputs and additional dataset for comparisons, the model’s predictive capability should improve further. If the input parameters are standardized and additional datasets are acquired, utilization of additional information such as recruit anthropometry and exercise history may be incorporated in the model leading to further accuracy. Parameter optimization and other complex statistical methods will likely help incorporate the additional data. Note that the current version of

the model is unable to predict stress fracture rates for various training regimes. Nevertheless, OIM 1.0 appears stable and this first version has demonstrated the capability of modeling stress fractures.

7. Additional Developments

In addition to stress fracture injuries, recruits may benefit from modeling the metabolic (energy) requirements and performance gains of basic training. Although the current development focus was on stress fractures, several inroads on metabolic and performance have been made. Recently, initial and final physical fitness results were acquired for a sample of MCRD San Diego recruits. Measures include pull-up, crunches, and run times. Individual scores for all recruits have been kept for approximately the last eighteen months. With such extensive records, it may be possible to relate physical fitness changes to the current training regime using an approach similar to that used for stress fractures. In addition, a regression equation relating metabolic cost to muscle force was recently published based on the investigation into metabolic requirements of basic training.[1] This equation may allow metabolic cost to be estimated for a wide variety of training regimes. Also, in an effort to acquire more accurate training distances, an enhanced GPS-based tracking system (Point Research, Inc.) was purchased and loaned to MCRD San Diego for assessment but testing has not yet been completed.

[1] Sih, B. L. and J. H. Stuhmiller (2003). "The metabolic cost of force generation." Medicine and Science in Sports and Exercise **35**(4): 623-629.

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